Low-level pulsed 1064 nm laser radiometer transfer standard

Rodney W. Leonhardt

National Institute of Standards and Technology
325 Broadway, Boulder, Colorado 80303

ABSTRACT

The National Institute of Standards and Technology (NIST) has developed a low-level peak power and pulse energy radiometer (APD 900) transfer standard for collimated laser light at a wavelength of 1064 nm. The peak power irradiance measurement range is from 500 pW/cm^2 to 50 µW/cm^2 for laser pulse widths of 10-250 ns. The pulse energy measurement range is from 0.05 fJ/cm^2 to 50 pJ/cm^2. The instrument combines the functions of peak power and pulse energy measurement into one unit, and improves the responsivity by two orders of magnitude greater than previous NIST designs calibrated at1064 nm. The radiometer is based on an infrared-enhanced silicon avalanche photodiode with 100 mm diameter full aperture collecting optics. Selectable aperture sizes and a neutral density filter extend the measurement range of the instrument to higher levels, especially with large diameter beams. The output is a voltage waveform that can be measured with an oscilloscope. Calibration uncertainty for the APD 900 radiometer is typically less than ±8%. Improvements in the NIST calibration system will potentially lower the uncertainty to approximately ±5%.

Keywords: infrared, laser radiometer, peak power, pulse energy, 1064 nm

1. APD 900 RADIOMETER DESIGN

The basic design schematic of the low-level infrared laser radiometer is presented in Figure 1. Collecting optics focus collimated laser light onto an optical detector to provide a voltage signal that can be measured with an oscilloscope. The detector signal is calibrated in terms of Volts per Watt for peak power and can be amplified to increase the measurement range. Routing the signal through an integrating amplifier provides an output which is calibrated in units of Joules per Volt.

1.1 APD detector module

The optical transducer for the radiometer is a silicon avalanche photodiode (APD) which has been custom fabricated and optimized for near-infrared performance. The detector surface is dimpled to increase absorption of the incident radiation. The APD detector is packaged with a transimpedance preamplifier on the chip to perform the current-to-voltage conversion, amplify the signal, and provide temperature compensation of the responsivity.

0-8194-2203-7/96/$6.00

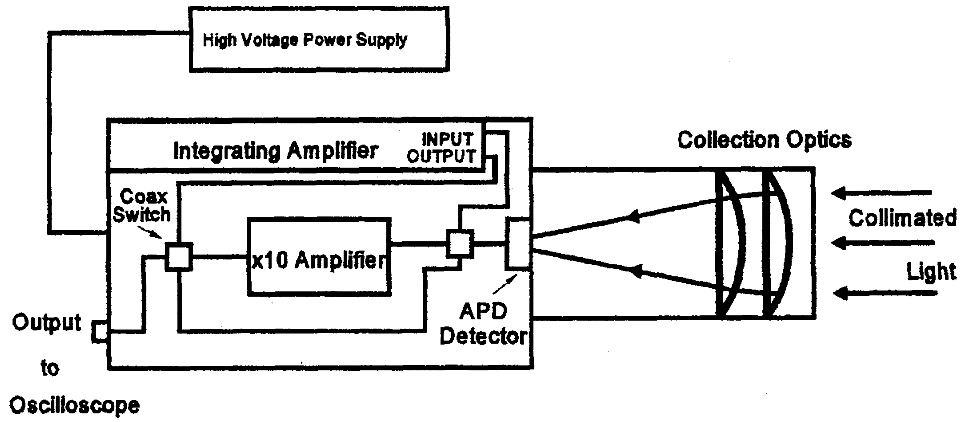

Figure 1 APD 900 radiometer schematic

The on-chip temperature compensation was insufficient for the accuracy and stability required, so an external temperature control was provided. This was implemented by mounting a resistance heater coil in physical contact with the APD module. Thermistor sensors and control circuitry provide temperature stability to $\pm 1\,^{\circ}C$, at a set point near $40\,^{\circ}C$. The controller provides heating only, so the ambient temperature must be lower than the set point, if the detector response is to be stabilized.

The APD package is hermetically sealed, with a narrowband antireflection coated window at 1064 nm. The active area is 3 mm in diameter, and the bandwidth is 45 MHz as specified by the manufacturer. A bandwidth of at least 40MHz was necessary to meet customer requirements for measuring peak power of laser signals with pulse duration of approximately 20 ns. Even this was a compromise of the performance specifications for sensitivity and rise time. The resulting rise time or impulse response was not fast enough to replicate 20 ns signals accurately. This pulse distortion required an impulse response test and the use of correction factors for compensation because the low-level system is presently capable of calibrations with pulse durations no narrower than 200 ns.[1]

1.2 Collection optics

Overall system responsivity is increased for large diameter beams by the optical front-end. A fully open aperture of 10 cm diameter allows the radiometer to measure laser pulses with peak irradiance down to 500 pW/cm^2 for peak power irradiance and 0.05 fJ/cm^2 for pulse energy density. Peak irradiance responsivity is a factor of 100 better than previous NIST designs. This instrument measures peak irradiance at a level five orders of magnitude below the capability of commercial off-the-shelf laser radiometers available at the time of the design.[2]

All of the laser radiation entering the radiometer must converge on the detector's active area to perform absolute measurements. The light-collecting optical system consists of two identical plano-convex lenses separated by 5 mm, which focus the incoming collimated laser radiation. The APD detector is mounted where the light is focussed to its smallest spot size, that is, at the least circle of confusion. This smallest spot diameter is approximately 1-1.5 mm for a fully open aperture input.

The optical design using two plano-convex lenses was selected for practical performance reasons. The overall length of the optical system is roughly half that of using a single lens of the same focal length, making the size more manageable. Spherical aberrations are significantly reduced, allowing a large diameter beam to be entirely focussed onto the 3 mm detector. This two-lens design is also more robust in tolerating less than perfectly collimated light, compared to similar single-lens designs.

1.3 Amplifier electronics

1.3.1 Wideband amplifier for peak power measurements

Very low level electrical pulses can be boosted to a voltage suitable for an oscilloscope by selecting a 20 dB (x10 voltage) amplifier option. Customer requirements for peak power measurements on 20 ns pulses dictated the use of a fast, 750 ps rise time amplifier (500 MHz bandwidth) to maintain signal fidelity. The maximum linear signal from the detector or the amplifier is 0.7 V. The impulse response of the APD along with the amplifier was measured as discussed in Section 3.

1.3.2 Integrating amplifier for pulse energy measurements

Calibrated pulse energy measurements are made by sending the APD detector voltage output to a five-stage analog amplifier that electrically integrates the signal. The amplifier provides an output whose peak-to-peak voltage is linearly related to the laser energy for pulse durations less than 250 ns. The maximum calibrated linear signal is 1.25 V peak-to-peak.

2. MEASUREMENT CAPABILITIES

2.1 Measurement range

The APD 900 radiometer is calibrated for measurement of 1064 nm laser pulses with very low energy and peak power. The unit is designed to receive collimated laser light with diameters up to 10 cm. If the beam intensity cross section is uniform, then the peak irradiance or fluence can be measured for beams larger than the aperture. The external selectable apertures or a neutral density filter are used to reduce the absolute peak power to measurable values for larger diameter beams.

2.1.1 Pulse energy measurement range

The radiometer measurement range for absolute pulse energy is from 4 fJ to 10 pJ with input pulse durations of 15 to 250 ns. The apertures and neutral density filter allow fluences from 0.05 fJ/cm^2 to 50 pJ/cm^2 to be measured.

2.1.2 Peak power measurement range

The radiometer absolute peak power measurement range is 30 nW to 100 μW. Apertures allow the irradiance measurement to be extended from 500 pW/cm^2 with a fully open aperture to 50 μW/cm^2 using a neutral density filter. Response has been calibrated for pulse widths of 10-30 and 100-250 ns.

3. IMPULSE RESPONSE

Laser pulses narrower than 10 times the impulse response of the APD detector and external amplifier may have a distorted voltage waveform.[3] The peak voltage and pulse duration will be incorrect. In an attempt to account for these waveform modifications on short pulses, a table of correction factors was calculated by convolving the measured impulse response of the detector system with Gaussian pulses. The initial correction factors were calculated for peak pulse height and pulse duration for Gaussian pulses of 10-30 ns, Full Width Half Maximum (FWHM). Further investigation into the validity of the correction factors, and the effect of pulse shape on the calibration factor is continuing.

The impulse response of the APD 900 radiometer was measured using a 1.06 μm wavelength laser diode with a pulse width of 120 ps as the test signal. This test signal is fast enough to function as an impulse compared with the expected risetime of the detector, which was ~7 ns, estimated from manufacturer specifications.[4]

The detector output was logged using a 1 GHz bandwidth oscilloscope, which has a rise time of 0.35 ns, again much faster than the APD detector. Figure 2 shows a typical impulse response waveform from the APD detector package. The external 20 dB amplifier has maximum rise and fall times of 750 ps, which is much faster than the 7.5 ns impulse response of the APD detector. As a result, the impulse response of the detector and amplifier together is typically only 0.1 ns greater duration. A computer program was used to calculate the convolution of the impulse response waveforms with Gaussian pulses varying from 10 to 30 ns in duration.

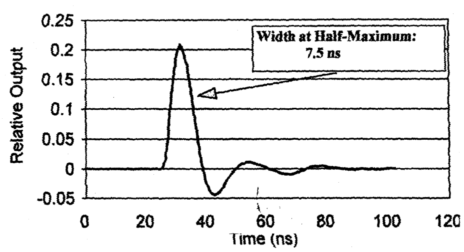

Figure 2 Typical impulse response of APD detector, without external amplifier.

Figure 3 graphs typical correction factors obtained for the APD detector using convolution calculations. These factors allow the observed or measured peak voltage and pulse width to be adjusted to give a more accurate response of the detector for 10-30 ns laser pulses.

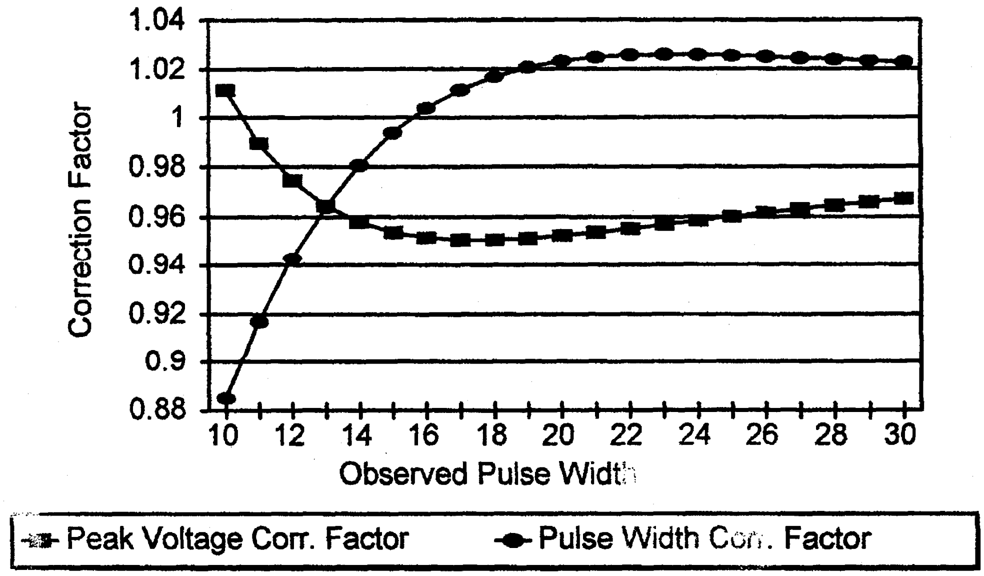

Figure 3 Typical peak voltage and pulse width correction factors.

4. SUMMARY

A specialized radiometer has been designed, built, and characterized for measuring very low levels of pulsed laser radiation produced by Q-switched lasers operating at a wavelength of 1064 nm. The APD 900 radiometer voltage output signal is calibrated for both peak power and pulse energy measurements. The impulse response has been measured, and correction factors calculated for pulse widths ranging from 10 to 30 ns.

Total calibration uncertainty for the voltage output of the instrument is typically less than ±8% and is calculated according to NIST guidelines.[5] A large part of the uncertainty results from Type B or systematic uncertainties in the calibration system. Improvements to the NIST low-level 1064 nm calibration system are being developed with the goal of reducing the uncertainty to less than ±5%. The ability to calibrate the radiometer directly with 20 ns pulses is being developed to verify the accuracy of the calculated correction factors and to lower the total uncertainty.

5. ACKNOWLEDGMENTS

This work was supported by the U.S. Naval Warfare Assessment Division and the U.S. Army Primary Standards Laboratory.

6. REFERENCES

1. A.L. Rasmussen and A.A. Sanders, "Transfer Standards for Energy and Peak Power of Low-Level 1.064 Micrometer Laser Pulses and Continuous Wave Power," Optical Engineering, Vol. 25 No .2, pp. 277-285, Feb. 1986.

2. J.W. Walden and D.L. King, "Low Level Peak Power Radiometer," Proceedings of the 1993 Measurement Science Conference, (complete reference data unavailable).

3. K.D. Li Dessau, "Insights into High-Speed Detectors and High-Frequency Techniques," Application Note 1, New Focus Inc, Mountain View, CA, 1991.

4. Rise time calculation = 0.35/Bandwidth, "11401 and 11402 Digitizing Oscilloscopes User's Reference Manual," Tektronix, Inc, p. 4-16, Beaverton, Oregon, May 1988.

5. B.N. Taylor and C.E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology Technical Note 1297, 1994.